

Cosmic Accretion

Greatest opportunity in astrophysics

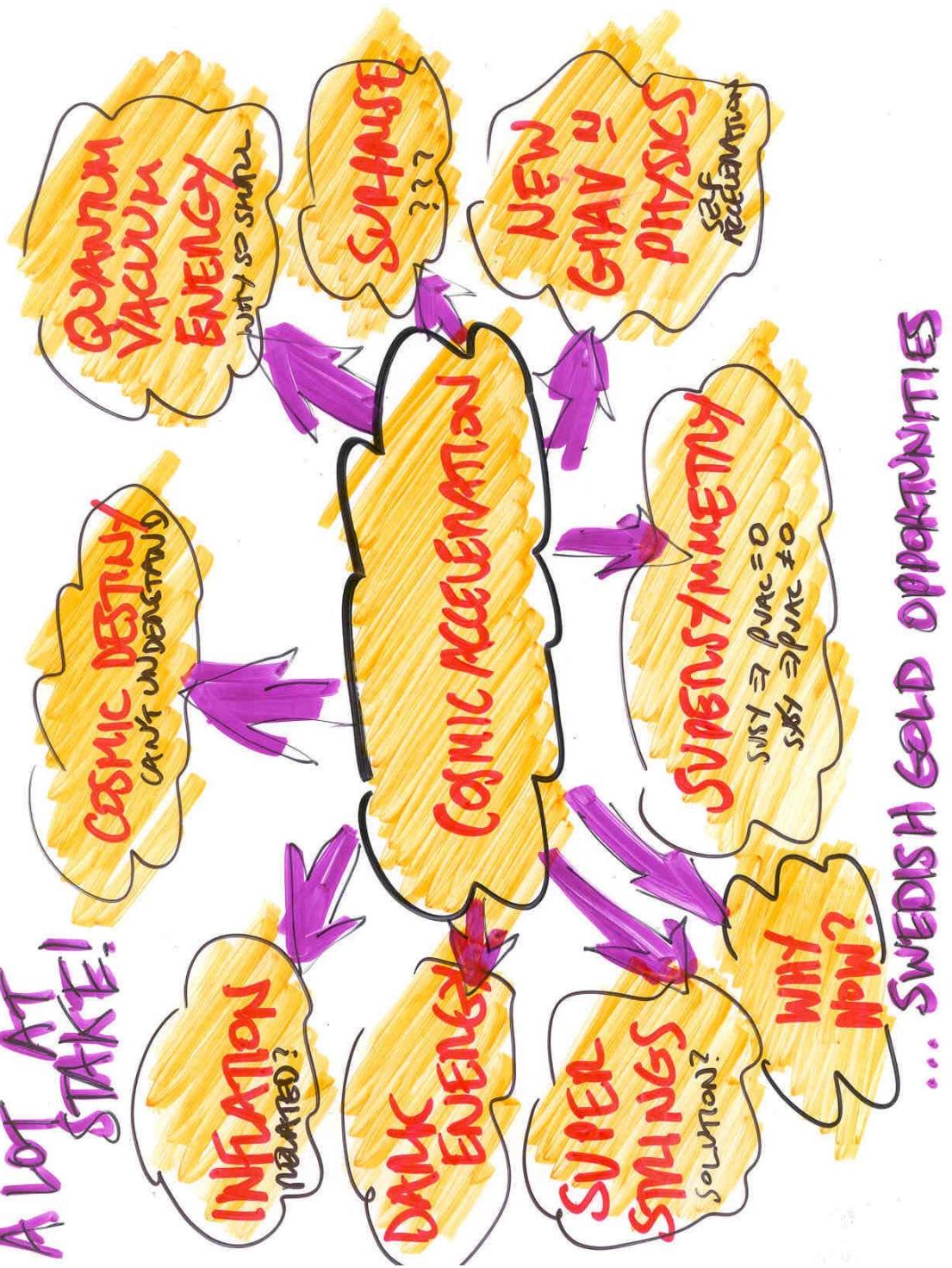
Not too good to be true!

Deep & profound connections

Mysterious dark energy or new
gravitational physics

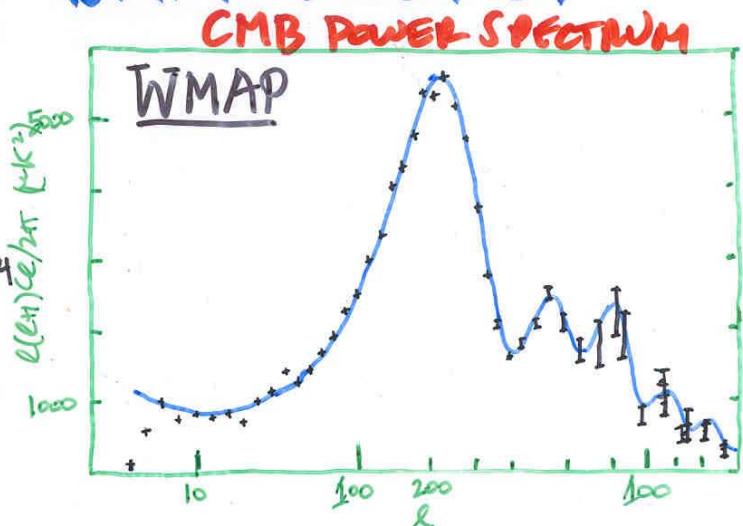
Cosmology is the best place we
know of

A LOT AT STAKE!



INDEPENDENT TWO LINES OF EVIDENCE FOR DARK ENERGY

CMB →
"MISSING ENERGY"
 $\Omega_X = \Omega_0 - \Omega_M$
 $= 0.7 \pm 0.04$

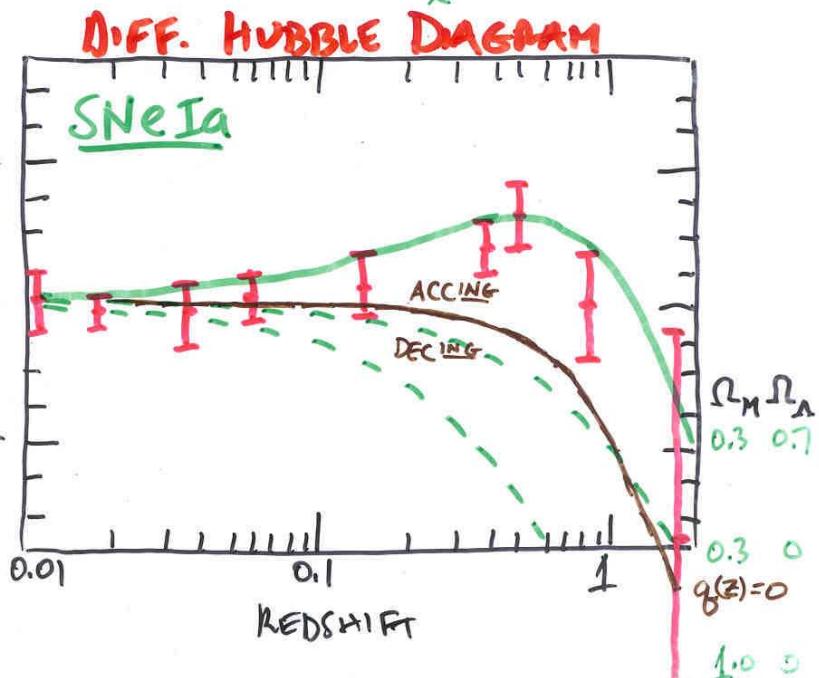


SNe Ia

200 SNeIa
astroph/0305008
(Tonry et al.)

$\Omega_X =$
 $1.4\Omega_M + 0.35$
 ± 0.14

$= 0.8 \pm 0.06$



EARLY PERIOD OF Deceleration

BETONE
SPEED UP

TUNNELING-
Higgs 2003

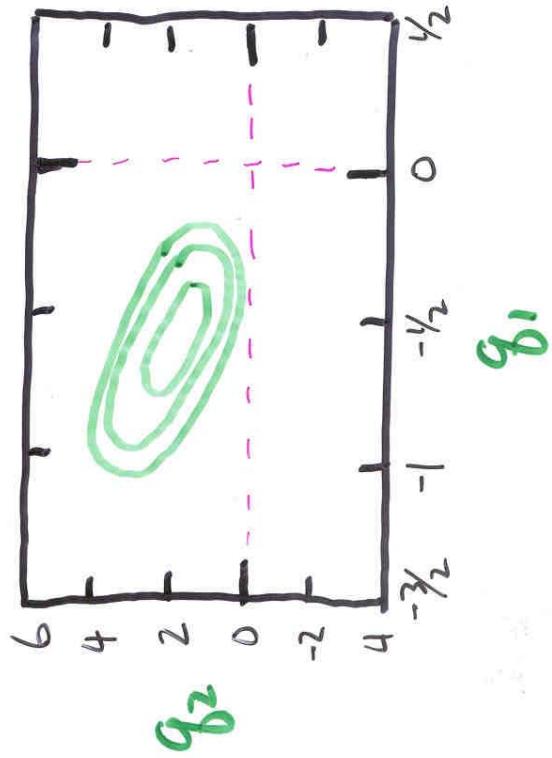
JK HTS SNE $Z \approx 0.9 - 1.8$

$g_1 = \text{AVERAGE DECELERATION}$
SINCE $Z = \frac{1}{2}$ (LAST 5 Gyr)

$g_2 = \text{AVERAGE DECELERATION}$
EXCEPT THAT $Z = \frac{1}{2}$
(FIRST 9 Gyr)

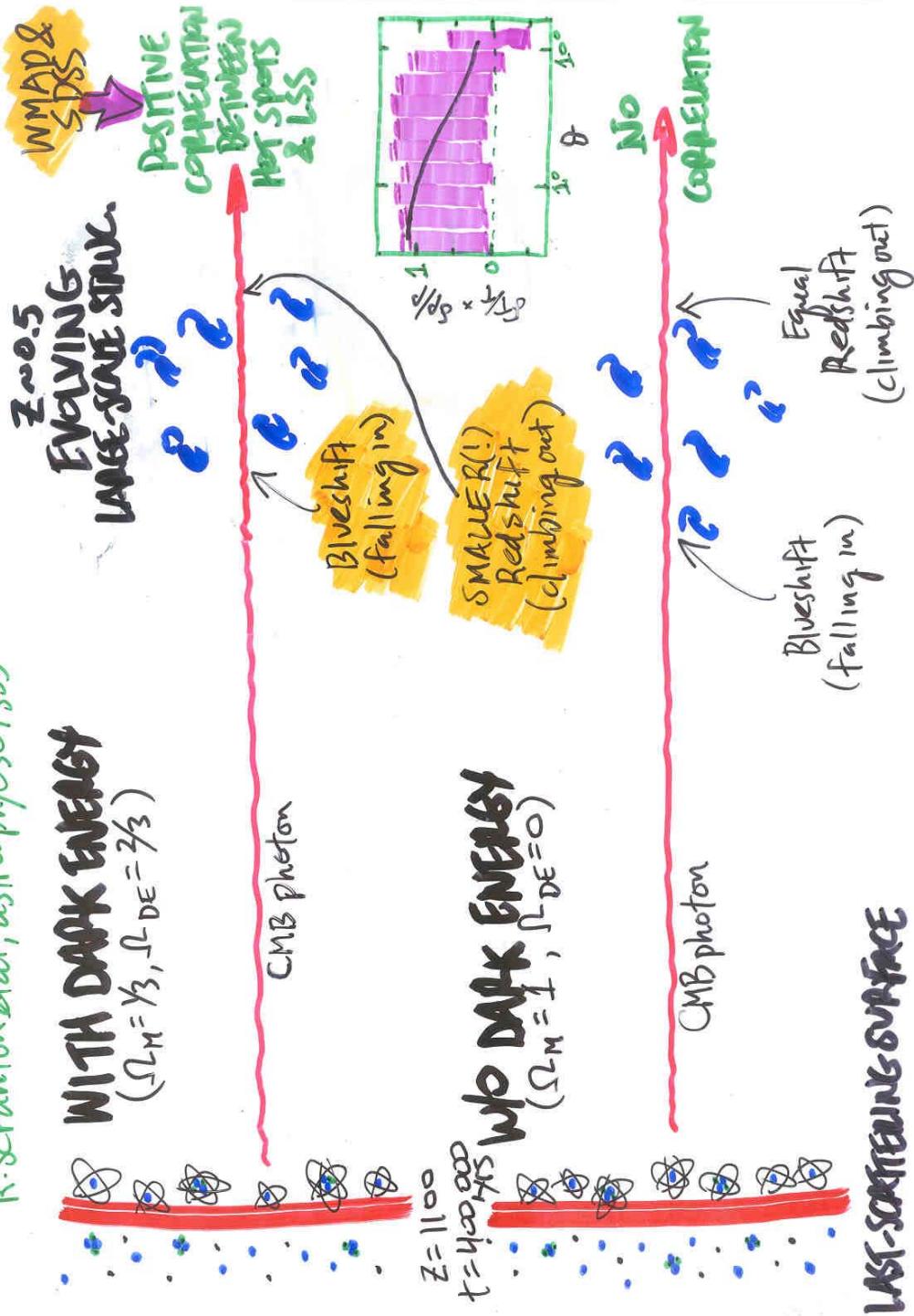
$$g_1 \approx -\frac{1}{3} \text{ RECENT AC.}$$

$$g_2 \approx 1 \text{ PAST DECEL.}$$



DETECTING DARK ENERGY w/ SACKS-WAFFS EFFECT

R. Scranton et al., astro-ph/0307355



GR ALLOWS FOR REPULSIVE GRAVITY:

SOURCE OF GRAVITY IN GR:

$$\rho + 3p$$

(SPATIAL SYMMETRY)

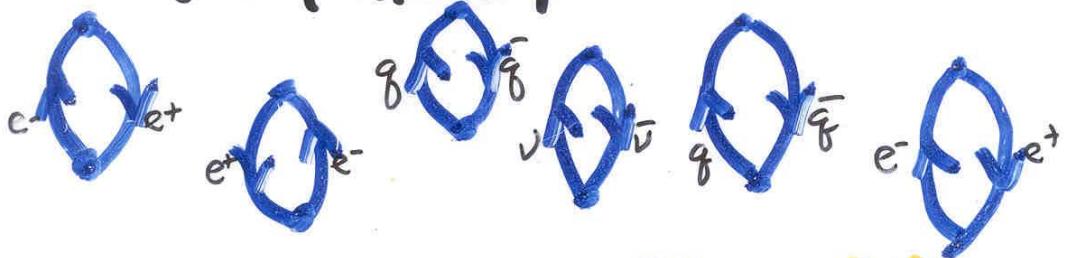
FEATURE
NOT A
BUG!

→ BLACK HOLES WHEN
 $p \geq p/3$

→ REPULSIVE GRAVITY
WHEN $p < -p/3$

QUANTUM VACUUM IS NOT EMPTY!

sea of virtual particles



whose existence has been detected
(shifting of atomic levels in H)

W. LAMB, Nobel Prize '55

Quantum vacuum is elastic ($p = -p$)
& its Gravity is ^{VERY} Repulsive! ($p + 3p = -2p$)

JUST WHAT IS NEEDED -- BUT ...
THEORETICAL ESTIMATES OF AMOUNT

$10^{55} \times$ what is needed to
explain accelerating Universe

"Houston, we have a problem"

**SOLVING THE CRAZY
PROBLEM WILL REQUIRE
ACRAZY, NEW IDEA !**

NB: NOT EVERY CRAZY IDEA IS A SOLUTION
ONLY?

**CRAZIER IS THE BEST PROBE
OF DARK ENERGY**

CHARACTERIZING DARK ENERGY

- UNCLUSTERED
- $\Omega_X = 0.7 \pm 0.04$

- $w \equiv p_x/\rho_x$

SIMPLE, AD HOC
DESCRIPTION

$$\rightarrow P_x = \Omega_X P_{\text{crit}} e^{3 \int (1+w) dz}$$

$$= \Omega_X P_{\text{crit}} (1+z)^{3(1+w)} \quad (\text{CONST } w)$$

SIMPLEST, BUT
THEONLY PREDICTS
 $\Omega_X \gtrsim 10^{55}$

DARK ENERGY CANDIDATES

	w	$w' = dw/dz$
VAC ENERGY	-1	0
TANGLED DEFECTS	$-1/3$	≈ 0
QUINTESSENCE	$-1 \rightarrow 1$	$\neq 0$
"GHOSTLY QUINT."	< -1	$\neq 0$
NEW GRAV PHYS	< 0 , imaginary!	$0, \neq 0$

NO DARK ENERGY
NEW ASPECT OF GRAVITY

"A" EMPTY UNIVERSE
UNDERGOES ACCELERATED EXPANSION!

AVERAGE MATTER DENSITY TODAY $\gamma \approx 10^{-29} \text{ g/cm}^3$
 $\approx 10^{-100} \times$ DENSITY AFTER INFLATION

A MODEL FOR NEW GRAVITY PHYSICS

Duvvuri et al., astroph/0306438

Effective Action:

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{g} \left(R - \mu^4/R \right) - \int d^4x \sqrt{-g} L_m$$

↑
tiny correction
 $\mu \sim H_0 \sim 10^{-42} \text{ GeV}$
dominates at late times

$$3H^2 = 8\pi G \rho_M + \frac{\mu^4}{12(H+2H^2)^3} [2H\ddot{H} + 15H^2\dot{H} + 2\dot{H}^2 + 6H^4]$$

Conformal Theory $\tilde{g} = p(\phi) g$ $p(\phi) = e^{\frac{2\phi}{3} \frac{\dot{\phi}}{M_p}}$
 Einstein + scalar field + "conformal matter"

$$3\tilde{H}^2 = 8\pi G (\rho_\phi + \tilde{\rho}_m)$$

$$\rho_\phi = \frac{1}{2} \dot{\phi}^2 + V(\phi)$$

$\phi_i \approx 0, \phi'_i > \phi'_{ic}$	$\phi(t \rightarrow \infty) \rightarrow \infty$	$a(t) \sim t^2$ ($w_{DE} = -\frac{2}{3}$)
$\phi_i = \phi'_{ic}$	$\phi(t \rightarrow \infty) = \phi_{max}$	de Sitter
$\phi'_i < \phi'_{ic}$	$\phi(t \rightarrow \infty) = 0$	future singularity

Fixes:

- MORE COMPLICATED ACTION \Rightarrow
 $V(\phi)$ w/stable minimum
("massive extra degree of freedom")
- ADD DERIVATIVE TERMS TO ACTION
TO CANCEL \dot{H} , \ddot{H} terms

HIGHER DIMENSIONAL MODELS

Deffayet, Dvali & Gabadadze astro-ph/0309068

IR modified gravity (propagator approach)

$$H^2 = \frac{8\pi G \rho_M}{3} + H/r_c \quad r_c = \frac{H_0^{-1}}{(1-\Omega_M)}$$

$$w \rightarrow \begin{cases} -1 & t \rightarrow \infty \\ -k & t \rightarrow 0 \end{cases}$$

COSMIC SPEEDUP: THREE BIG QUESTIONS

1. Why is ρ_{vac} so small?
2. Why now?
3. Cosmic destiny?

A GOOD SOLUTION
SHOULD ADDRESS
ALL THREE

DARK ENERGY MODELS

1. Small vacuum energy

- SYMMETRY + FALSE VACUUM
- BROKEN SYMMETRY e.g. SUSY
- MULTIVERSE + LOCAL BY LAWS + $\mathcal{L}(\mathbf{E}|\Delta\ldots)$

3/3 SOLVED

2. "Static solns"

- FRUSTRATED NETWORK OF DEFECTS

$$w = -1/3$$

1/3 (DESTINY ONLY)

3. Dynamical models

- QUINTESSENCE, K-ESSENCE, ...

1/3 (DESTINY ONLY)

4. New Grav Physics

"EMPTY SPACE IS SELF-ACCELERATING"

2/3 (NOT SMALL VAC ENERGY)

DARK ENERGY & COSMOLOGY

PRIMARY EFFECT: EXPANSION RATE

$$(\dot{R}/R)^2 = H(z)^2 = H_0^2 [\Omega_M(1+z)^3 + \Omega_X(1+z)^{3(1+w)}]$$

ASSUMING FLAT UNIVERSE SO THAT $\Omega_X = 1 - \Omega_M$

NB: $H(z)/H_0 = f(\Omega_M, w)$ TWO PARAMETERS

SECONDARY EFFECTS :

DISTANCES

$$r(z) = \int_0^z \frac{dz'}{H(z')}$$

$$d_L \equiv (1+z)r(z) \equiv \left(\frac{z}{4\pi F} \right)^{1/2}$$

GROWTH OF STRUCTURE

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G \rho_M \delta = 0$$

$$\delta = (\delta/\rho)_k, \text{ linear regime}$$

THREE COSMOLOGICAL PROBES

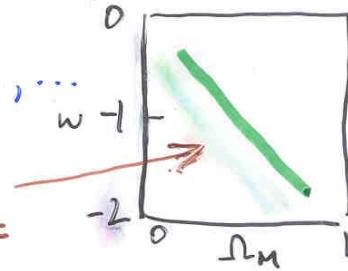
(1) STD CANDLES

e.g. SNe Ia

- + no cosmological sys
- astrophys sys: dust, evol., ...

$r(z)$ vs. z

ASSUMPTIONS: metric theory + std candle



degeneracy: line of fixed r @ $z = 1$:
 $3W + \Omega_M = \text{const}$

(2) EVOL OF STRUCTURE

e.g. as probed by W.L.

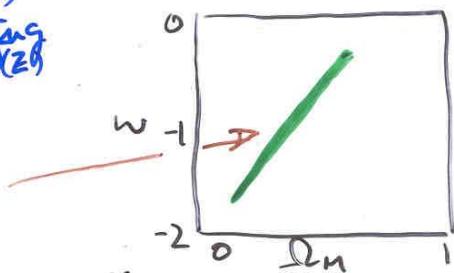
^{sys.}

- + no astrophys. sys. (intrinsic alignment?)
- instrumental sys, modeling of $\delta(z)$

$\delta(z)$ vs. z

ASSUMPTIONS: metric theory +

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G p_m \delta = 0$$



degeneracy line:
fixed growth $z=1 \Rightarrow z=0$
 $4w - \Omega_M = \text{const}$

(3) COUNTING "COSMIC FROGS"

e.g. clusters vs. z

- + exp. sensitivity to $\delta(z)$,
cting is easy

ASSUMPTIONS: metric theory +

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G p_m \delta = 0 + \text{Gaussian } \delta p/p$$

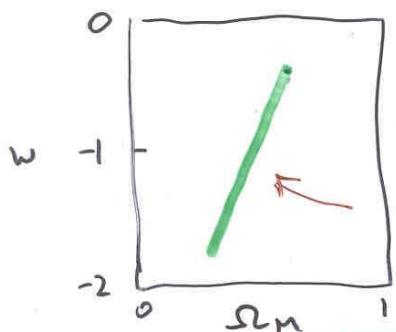
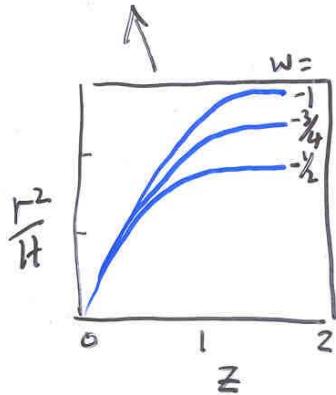
- determining cluster masses,
theoretical modeling

dN/dz vs. z

$$\frac{dN}{d\Omega dM dz} = \frac{dn}{dM}(z) \times \left(\frac{dV}{dz d\Omega} = \frac{m(z)^2}{H(z)} \right)$$

THEORY:

$$\sqrt{\frac{\pi}{\lambda}} \frac{p_m}{m} \frac{\delta c}{\sigma(M, z)^2} \frac{d\sigma}{dM} e^{-\delta_c^2/2\sigma^2}$$



fixed $dN/dz @ z=1$

$$\approx 4w - \Omega_M = \text{const}$$

SUMMARY

3 METHODS, 3 DIFF. SET OF ASSUMP.

3 DIFF. SETS OF SYSTEMATICS

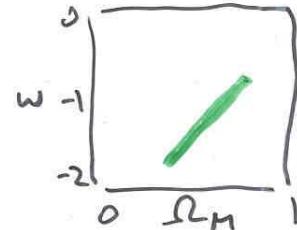
 COMPLEMENTARY,
SIMILAR PRECISION: $\Omega_W \sim 0.05$ $\Omega_W \sim 0.1$

SECONDARY PROBES

• CMB Anisotropy

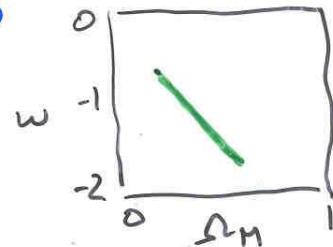
Position of acoustic peaks

- + SIMPLE PHYSICS
- STRONG DEGENERACY
- NO SENSITIVITY TO w'



• Age of Universe

- + INDEPENDENT METHOD
- SYSTEMATICS
- NO SENSITIVITY TO w'



• Clustering of Dark Energy

- + GETS AT NEW PROPERTY
- VERY SMALL EFFECT, ON VERY LARGE SCALES

SIGNATURES OF PHYSICS BEYOND VACUUM ENERGY

$w \neq -1$ $\dot{w} \neq 0$ CLUSTERING

COSMIC PROBES OF DARK ENERGY

METHOD

ASSUMPTIONS

MEASURES

ESTIMATED
POTENTIAL

$$SN Ia = "STD CANDLE"$$

$$r(z)$$

$$\bar{\Omega}_w = 0.05$$

$$\bar{\Omega}_{w'} = 0.15$$

EVOLUTION
SN DIVERSITY
DUST

$$\text{NON-LINEAR} \\ \text{CDM POWER SPECTRUM} \\ = f(D_2, n, \Omega_8, \dots)$$

$$\delta(z) \\ r(z), H(z)$$

WEAK-
LENZING
"shear"
EVOL. OF
STRUCTURE

ANISOTROPY
OF P.S.F.
DUE TO SKY +
OPTICS

$$\bar{\Omega}_w = 0.03$$

$$\bar{\Omega}_{w'} = 0.1$$

$$S-z, \\ X-ray, W-L \\ \text{CDM POWER SPECTRUM} \\ \text{GAUSSIANITY} \\ r(z)^2/H(z) \\ \delta(z)$$

$$r(z)^2/H(z) \\ \delta(z)$$

SEE ABOVE
IN IN-T

DEEP FIELD
SHIFT SHEAR
CARTOONS, CLUSTERS

$$r(z)^2/H(z)$$

GALAXY
MATTER
EVOLUTION

$$\bar{\Omega}_w = 0.05 - 0.10$$

$$\bar{\Omega}_{w'} = 0.2$$

$$r(z=1100)$$

$\Omega_m - w$
DEGENERACY

$$\bar{\Omega}_w = 0.2$$

NB: DARK ENERGY DEPOLARIZED BY $\frac{d\theta}{dz} = w(z) = w + w'$